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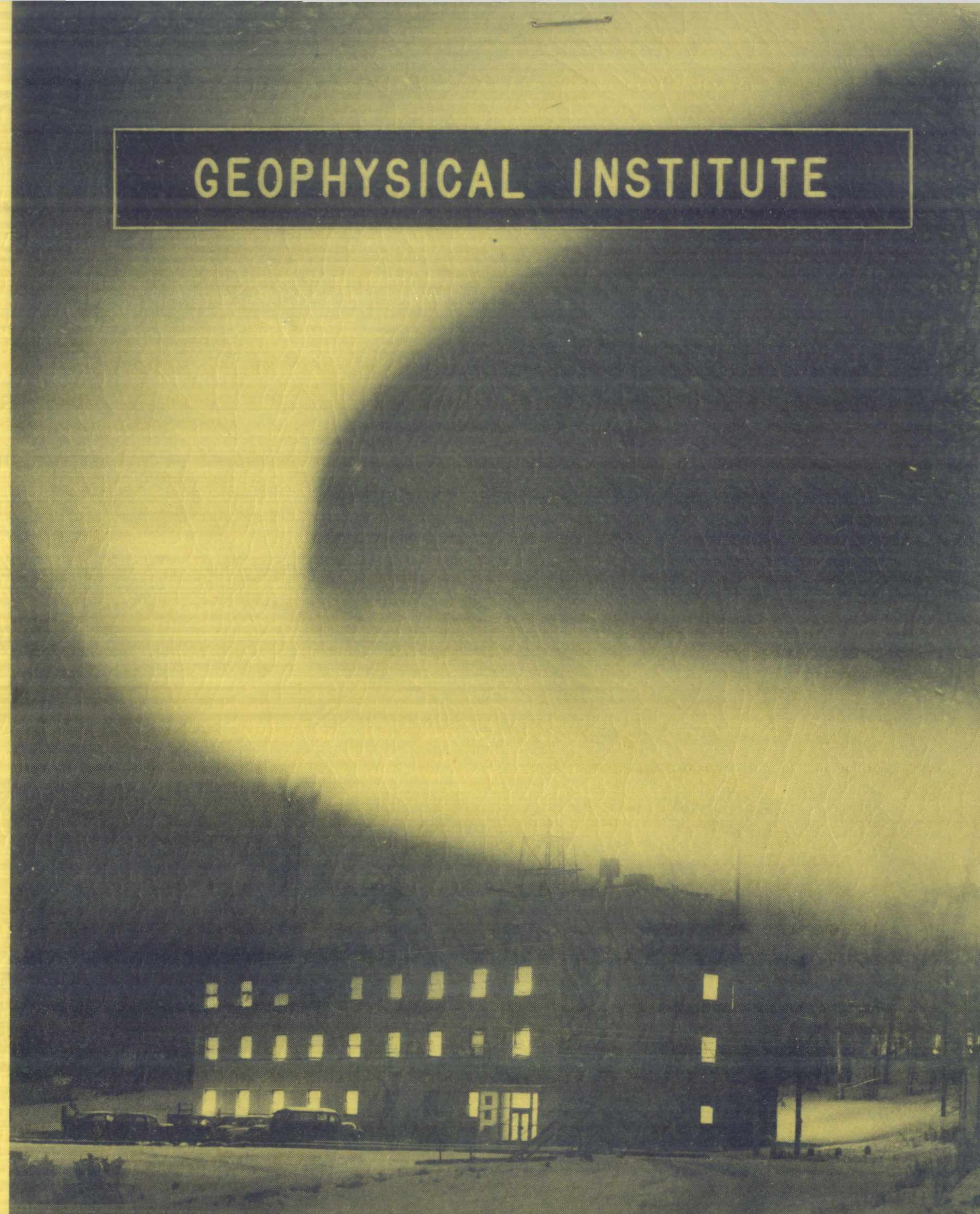

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PHOTOMETRIC STUDIES OF AURORAL LUMINOSITY AND ITS CONNECTION WITH SOME ATMOSPHERE IONIZATION PHENOMENA

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ABSTRACT

The auroral radiation, 3914 Å, received from the entire sky on a horizontal diffusing plate was monitored continuously during the nights of 1955-56 and 1956-57. The 1955-56 data and part of the 1956-57 data were used to obtain a diurnal curve for the sky luminosity in this wavelength. The auroral light increases to a broad maximum which lasts from magnetic midnight till dawn. The luminosity was found to correlate fairly well with absorption as inferred from F-min values and with $(F\ E_s)^2$ and very well with the magnetic K indices.

INTRODUCTION

The auroral radiation at λ 3914 Å originates from the ionized nitrogen molecule. Since the molecule is probably excited at the time it is ionized, it seems likely that the intensity of radiation at this wavelength will be related to the rate of production of free electrons in the auroral region. (There are other means by which free electrons may be produced, however, some of which are related to the auroral display and also some which have no relation to auroral processes.) Beside being a direct measure of the rate of production of electrons from nitrogen molecules, the intensity of 3914 Å radiation should also be proportional to the intensity of the exciting agent.

The intensity of the 3914 radiation received from the whole sky was monitored continually during the winters of 1955-56 and 1956-57.[1] This was done by means of a photoelectric photometer which observed a horizontal matte surface exposed to light from the entire sky. The photometer was fitted with a Baird interference filter with the appropriate Corning glass filter. Half intensity width of the combination was about 150 Å. The photometer consisted of a telescope which put an out of focus image on the photo-cathode of a 1P21 photomultiplier tube. The signal from the 1P21 was passed through a DC amplifier to an Esterline Angus recorder. Recording was at a tape speed of 6" per hour.

The 3914 Å region is on the edge of the ultra violet, and consequently is much less subject to interference from moonlight than would be the case with a longer wavelength. The moon does affect the readings however, because of the width of the filter pass band. In most instances it is possible to make corrections for this.

Cloud cover does not generally affect the observations greatly, because the auroral radiation is not absorbed by the clouds, but only scattered, and hence produces the effect of nearly the same amount of light arriving from a larger area. The high albedo of the cloud surface is somewhat compensated by the fact that auroral light is scattered toward the instrument from the whole cloud surface. The precise effect of cloud cover is not known, but comparison of observations on clear and cloudy nights suggest that the cloud effect cannot be large. A combination of moon and clouds, however sometimes renders the records unuseable, particularly if the clouds are broken.

The records were in the form of a luminosity-time curve which was scaled by taking the mean value of the luminosity over appropriate time intervals. The 1955-56 data was scaled in 5 minute intervals, which could be added to obtain hourly values, and so on for longer periods. This type of scaling gives essentially the integral of the luminosity time curve for the period in question. The 5 minute intervals required an excessive amount of scaling time, and the scaling of later data was done in 15 minute intervals. Much data remains to be scaled but enough has been processed to warrant some analysis.

The data have been used in the following studies: an analysis of the diurnal variation of the luminosity; a correlation between the luminosity and magnetic activity; a correlation between luminosity and sporadic E ionization (measured by the square of the maximum frequency returned by the E region); and a correlation between absorption (as indicated by the minimum frequency returned on the C-3 Ionosonde) and the 3914 Å luminosity. A study was also made of the relation between "no echo" conditions and auroral luminosity.

I. DIURNAL VARIATION

The question of the diurnal variation of auroral activity is of considerable interest in the theory of magnetic storms and aurorae. Observations on this point are not in very good agreement, even when they refer to the same geographic location. (2,3) The observations for College for 1933-34 for instance show a definite maximum at midnight followed by a sharp decline toward morning. Those for College in 1951-53 on the other hand, show an increase to about local midnight after which the activity remains high until daybreak. Since both sets of observations refer to periods of low solar activity, the reason for the difference is not clear.

The studies above refer to visual observations of aurora, and are therefore somewhat different than those considered here. The principal difference is that the photometric observations tend to give more weight to weaker forms of large areal extent than do the visual observations. The photometric maxima refer to the times when the maximum number of λ 3914 photons were received from the sky, without regard to whether they came from a small bright spot, or a large faint one, while the visual observations are apt to overlook the fainter forms when bright ones are present.

Fig. 1 shows the average luminosity vs time curve obtained from the data for 1955-56 plus the first part of the next winter (through December 1956). In view of the difference between the visual and all-sky photoelectric observations it is of interest to note the similarity between the 1951-53 visual data and the 1955-57 photoelectric data. It agrees quite well with the activity curve obtained by Elvey's group.

The fluctuations after the 0100-0200 period (150° West Meridian Time) are small and more or less random, so that one would be inclined to expect them to disappear in a larger sample of data were it not for the 1933-34 observations which indicate that the diurnal variation may change with time. However, it may be concluded that, at least throughout the period 1952-57, the auroral activity at College followed substantially the same diurnal curve, a build up during the early evening, reaching a high level at about magnetic midnight, after which the level remained constantly high until daylight ended the observations. The shape of this curve is not changed by the magnitude of the disturbance,[1] and it is not markedly affected by the season of the year. In Fig. 2, the average intensity vs time curves for each month of the observing season 1955-56 are shown. It can be seen that all are very similar to Fig. 1. It might be mentioned that any particular display will have several maxima of activity, and that a storm lasting several days may show that quite high auroral activity is present when it becomes dark enough to observe. In such cases, however, the activity still increases in intensity until about magnetic midnight. It is evident therefore, that the activity must decrease sometime after sunrise, and it seems probable that it follows the other magnetic storm phenomena and shows a quiet period in the afternoon.

Correlation between the College K indices (3 hr.) and the 3914 luminosities was quite good. Although the three hour periods used for the K indices did not necessarily coincide with the times during which photometric observations were made, a total of 292 K index periods coincident with photometer scalings were analyzed. The correlation coefficient obtained from these data was 0.7.

It should be emphasized that the observations above relate to the luminous aurora, as distinct from the phenomena observed by radar techniques.

II. RELATION BETWEEN AURORA AND ABSORPTION

A considerable amount of interest attaches to the relation between auroral luminosity and various ionospheric phenomena. An elaborate study of some of thsese was made by Heppner, Byrne, and Belon[4] "The Association of Absorption and E_s Ionization with Aurora at High Latitudes." In this work, visual observations were compared with ionospheric soundings, with particular reference to polar blackouts.* They found that when there was pulsating aurora at the zenith that blackout conditions prevailed some 70% of the time. More recently, Little and Leinbach,[5] observed that the absorption of 30 Mc extraterrestrial radio waves was more marked during periods of pulsating and flaming aurora. Comparison of the photometric records with ionospheric soundings by the C-3 did not show any very spectacular correlation between blackout conditions and pulsating aurora. However, closer examination shows that there is indeed a considerably higher percentage of pulsating aurora accompanied by blackout than is the case with non-pulsating aurora. During the winter of 1955-56, about 30% of the pulsating aurora which was detected by the photometers was accompanied by blackout. This is probably an upper limit, since the observing technique is not well suited to detection of pulsating aurora, and many such aurorae must have been undetected, the actual percentage accompanied by blackout being correspondingly less. On the other hand, the C-3 observations refer to the zenith, which is the most favorable area for detection of pulsating aurora by the photometers, so that the actual percentages may not be far off. It is not likely that any of the photometric observations refer to pulsating aurora which was outside the C-3 beam. The reason for the larger percentage observed in 1950-51 is not known, but it is believed to be partly a question of equipment parameters, because the 1950-51 observations show a very much larger total percentage of

*"Blackout as used here, means that no return signal was detected in the C-3 sounding.

blackout than do the 1953-56 observations. A possible clue also may lie in the fact that the earlier observations were during a period of lower auroral activity, about 35% of the observations showing no aurora as opposed to less than 25% in 1955-56.

In the 1955-56 data, 87 soundings with the C-3 ionospheric recorder which showed blackout conditions were accompanied by simultaneous photometric observations. Of these, 51 occurred after midnight and 36 before. Out of the total of 87 blackouts, 48 (55%) were during high auroral activity and only 12 occurred during times of extremely low auroral activity. The activities quoted refer to the hour preceding the time of the C-3 sounding. Pulsating aurora accompanied 45 C-3 soundings, 13 of these, or about 29% showed blackout. These 13 cases were all during periods of high luminosity. Only about 10% of the periods during which luminosity was at this level showed blackouts. The fact that the blackouts were associated with at least some aurora in 86% of the cases studied loses a considerable amount of its significance when one realizes that there was detectable aurora some 75% of the time. However, 26 of the blackouts (30%) occurred during levels of auroral luminosity which were reached only 7% of the time, and blackouts occurred during 22% of the cases at which activity reached this level.

The above can be summarized as follows:

Auroral Activity	High	Moderate-low	Very low-o
No. of blackouts	48	37	12

Condition	Pulsating aurora	Very High Luminosity
% of time accompanied by blackout	29%	22%

One can conclude from this, that the magnitude of the display is one of the important factors associated with blackouts.

Whether or not a particular sounding is classified as a blackout, is a matter of degree, and therefore, is apt to depend upon equipment parameters, operating, and scaling procedures etc. The actual point at issue is the question of the relation of luminosity in the auroral region to absorption at somewhat lower levels. In this connection, it is well to remember that failure to get a return signal can occur by reason of lack of ion density as well as by absorption. Examination of the critical frequencies around the time of blackout makes it seem probable that several of the occurrences classified as a blackout are indeed due to this condition, so that some of the events listed as blackouts with no aurora present are not true absorptive blackouts. Nevertheless, there are blackouts without associated aurora for which this explanation seems very unlikely, and it must be concluded that there are some actual absorptive blackouts, which, even though they occur long after sunset, have no obvious connection with corpuscular radiation which produces auroral luminosity or magnetic disturbance.

In the case of the absorption which is directly connected with the aurora, it is likely that the absorption comes about because short ultra-violet and soft X-radiation produces free electrons at levels below the E regions. Since quite intense bursts of X-radiation in the range up to 100 KEV have been observed to accompany the aurora,[6,7] it seems probable that it is this radiation which is responsible for the absorption. Winckler et al[8] believes that the X-radiation comes from a localized source, and that its intensity may be as high as 500 mr/hr at auroral altitudes. This would imply that the X-rays originate in the visible auroral forms themselves. This hypothesis is borne out by the fact that the X-ray intensity seemed to fluctuate in unison with the visible aurora, and that it was associated with the "break up" and active phase of the aurora.

X-ray intensities of this magnitude would certainly result in plenty of free electrons below the E region to cause blackout, and since they seem to be a usual feature of the aurora, the problem is not to explain auroral blackouts, but to explain why so many auroral events are not accompanied by blackouts. It seems probable that the answer lies in the geometry of the emission. Bremsstrahlung emission is not an isotropic process, the radiation being strongly concentrated in a direction which is determined by the nature of the target and by the direction and energy of the incident electrons.[9]

If the electrons are considered to be moving down the lines of force, and coincident with the luminous aurora, the emitting region will be a ribbonlike region, inclined about 12° to the vertical for the geomagnetic latitude or College area. The X-ray emission will probably not be intense over a large vertical extent because of the density gradient of the atmosphere. The effect of the asymmetry in the direction of X-ray emission will be to provide an intense "beam" of X-rays of whose horizontal cross section is somewhat less than the slant height of the emitting region on one side, and a beam from the upper side, whose horizontal cross section is broader and hence less intense. These maxima will be superimposed upon a more or less isotropic radiation of less intensity (see Fig. 3). The production of ions will depend upon the density of the air traversed and the spectral distribution of the X-rays, so that the precise form of the absorbing region is uncertain, but it probably has a considerable vertical extent, the effectiveness of the lower electrons being enhanced by the increased collision frequency.[10]

The absorbing regions then would be long ribbons, hundreds of kilometers in length, a few tens of kilometers in depth and a few tens of kilometers in width, embedded in a continuum of lower electron density. The ionization from the southern side of the auroral curtain would be much more intense and less spread in latitude. In fact, the geometry probably is such that the northern side produces mainly high level electrons and thus, is not so effective so far as absorption is concerned.

It can be seen therefore, that the ionization being produced at low levels (D region) at any one time would produce intense localized absorption. The aurora, however, is not stationary, and the actual area of the absorbing region will depend upon the rapidity of its motion and the lifetime of the free electrons it produces. The life-time of the free electrons depends strongly on height. Thus, the absorption produced by any particular auroral display at a given point depends on a number of factors, even though the total number of electrons produced in the D region may be a comparatively simple function of the magnitude of the luminous display.

To sum up, it seems as if the night time absorption in the auroral zone is generally, but not always associated with auroral activity. The part of the absorption which is connected with the visible aurora is probably a direct result of the increase in the number of free electrons resulting from the X-radiation of the aurora. In this case, the absorption would be expected to show a rough correlation with the brightness of the aurora, but because of its dependence on the previous events, and other factors, the correlation would not be expected to be too exact. The absorption produced by an auroral form 20° from the zenith, for instance would be very different if it were south of the zenith than if it were north, though the photometer readings would be much the same.

Little and Leinbach[5] showed that the f-min value (the lowest frequency at which a trace appears) obtained from the C-3 records was a fair indication of the amount of absorption present. The correlation between f-min and the intensity of λ 3914 radiation for the 5 minutes preceding the sounding was computed for the months of January and February 1956. For these two months, 232 pairs of values were available, and the correlation coefficient obtained from them was 0.43. Because it seems that the type of absorption which has no connection with auroral events is more prevalent before midnight, a correlation coefficient using only the 151 pairs of values from after midnight was computed. It turned out to be 0.54, which considering the number of values, can hardly be considered different than the one obtained from all the values. At any rate, the correlation is good enough to indicate that the mechanism outlined above is in fair agreement with the available data.

III RELATION BETWEEN AURORA AND SPORADIC E.

In the auroral zone, there is ionization of the sporadic type present most of the time in the E region. This is generally believed to be of a different nature than the "Sporadic E" ionization encountered in lower latitudes. Rawer,[11] suggests that this be called the "auroral layer" as it shows the same sort of diurnal variation as does the aurora. (The Canadian Radio Research Board and the National Bureau of Standards recognize the existence of a "Night-E" layer in auroral zone latitudes.) A preliminary study of the time correlation between sporadic E and auroral luminosity at College was done in 1955[12] This showed that for selected nights, the variation of FE_s (the highest frequency returned from the Sporadic E) followed that of the auroral luminosity quite well, also that sporadic E matched auroral activity on a daily basis.

Examination of the C-3 and photometric records for the period studied above showed that while most of the nighttime sporadic E observed at College seemed connected with the aurora, there appeared to be some which was not. In fact, many of the highest values of FE_s appeared to occur on nights which did not show any aurora. Again, as in the case of absorption, it must be concluded that although the aurora seems directly associated with most winter night sporadic E at College, there must also be some mechanism definitely not closely associated with the auroral luminosity which can result in sporadic E ionization. A correlation coefficient computed between $(FE_s)^2$ (since this should be proportional to the maximum density of free electrons) and auroral luminosity, using 145 C-3 soundings paired with the average luminosity readings for the five minutes preceeding the sounding gave 0.5, which is quite in line with the hypothesis that most, but not all the sporadic E ionization at College is of auroral origin.

A correlation of some 88 C-3 soundings with the luminosity average for the preceding hour, gave no apparent correlation. This would appear to indicate that the effect of the auroral ionization disappears quite rapidly, as would be expected.

Because of the geometry of the auroral luminosity it seems doubtful if the auroral E ionization is generally due directly to ionization by the incoming corpuscular radiation. The emission of 3914 Å radiation is almost certainly accompanied by the production of electrons, that is, the nitrogen molecule is excited at the same time it is ionized. The resultant ionization is quite dense, but would be in the form of a tilted ribbon. The bottom of this ribbon is the only favorable geometry for reflection and is probably less than 10 km wide in most cases, because of the rapid loss of the free electrons left behind as the auroral luminosity moves about. Reflections and backscatter from such areas would provide echoes on very high top frequencies, but would scarcely blanket the F region, as often occurs. On the other hand, the X-rays emitted from the north side of the aurora, because of the geometry already discussed, would have a direction of maximum emission which would be nearly horizontal. As a result, it could ionize over a very wide area, though not so densely as the X radiation from the south side of the ribbon. If the intensities of the X radiation are of the order of magnitude of those observed at Minneapolis, this radiation alone could probably account for most of the sporadic E electrons and also for the D region electrons which produce most of the auroral absorption. There is, however, another process which Chapman and Little[10] point out, namely the photo-detachment of electrons from O^- and O_2^- ions. This process requires very little energy and could be accomplished by any of the visible auroral radiations from λ 6300 on up, so far as energy is concerned.

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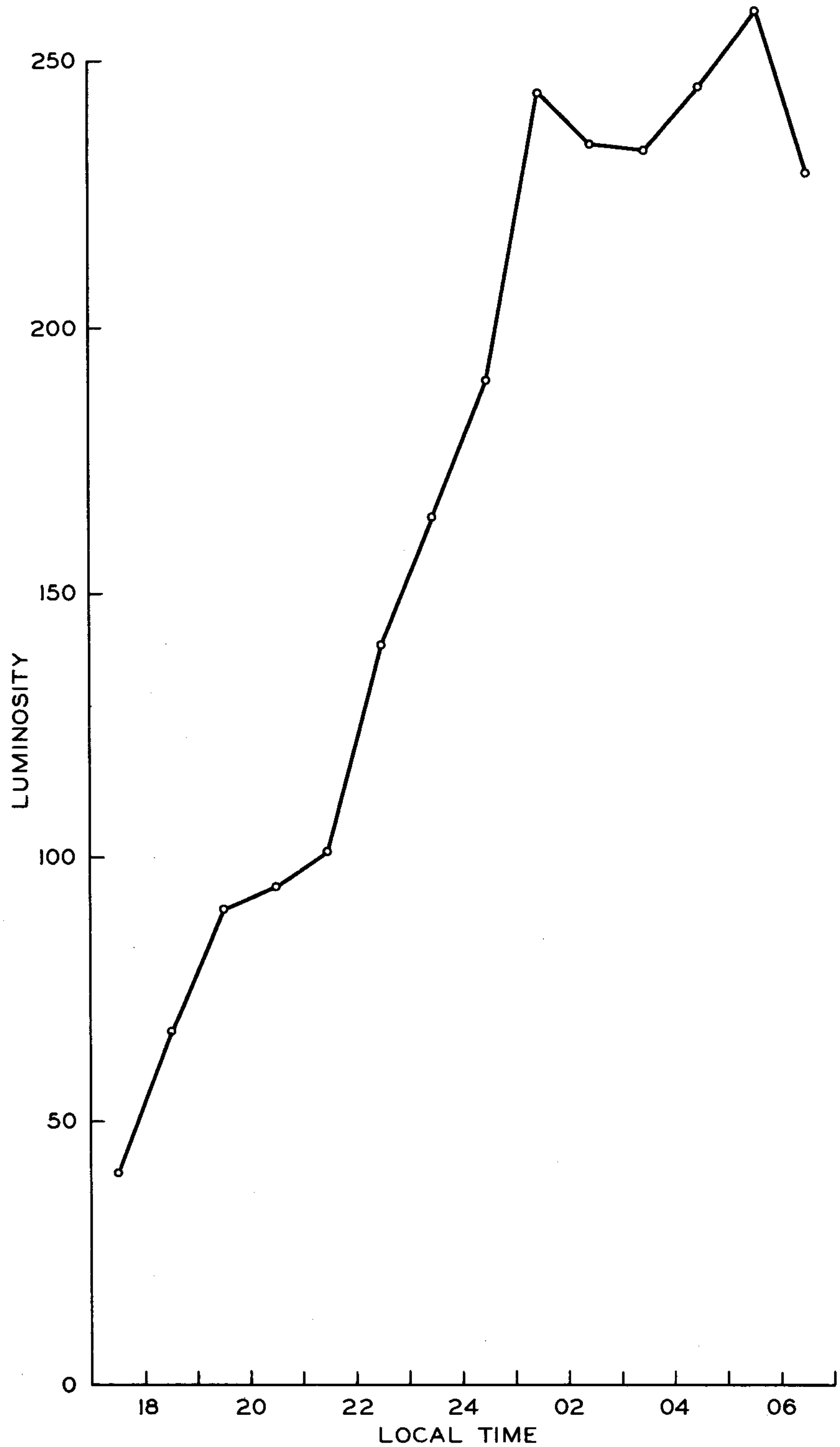

Fig. 1. Diurnal Variation of Sky Luminosity at 3914 Å

Luminosity Units Arbitrary

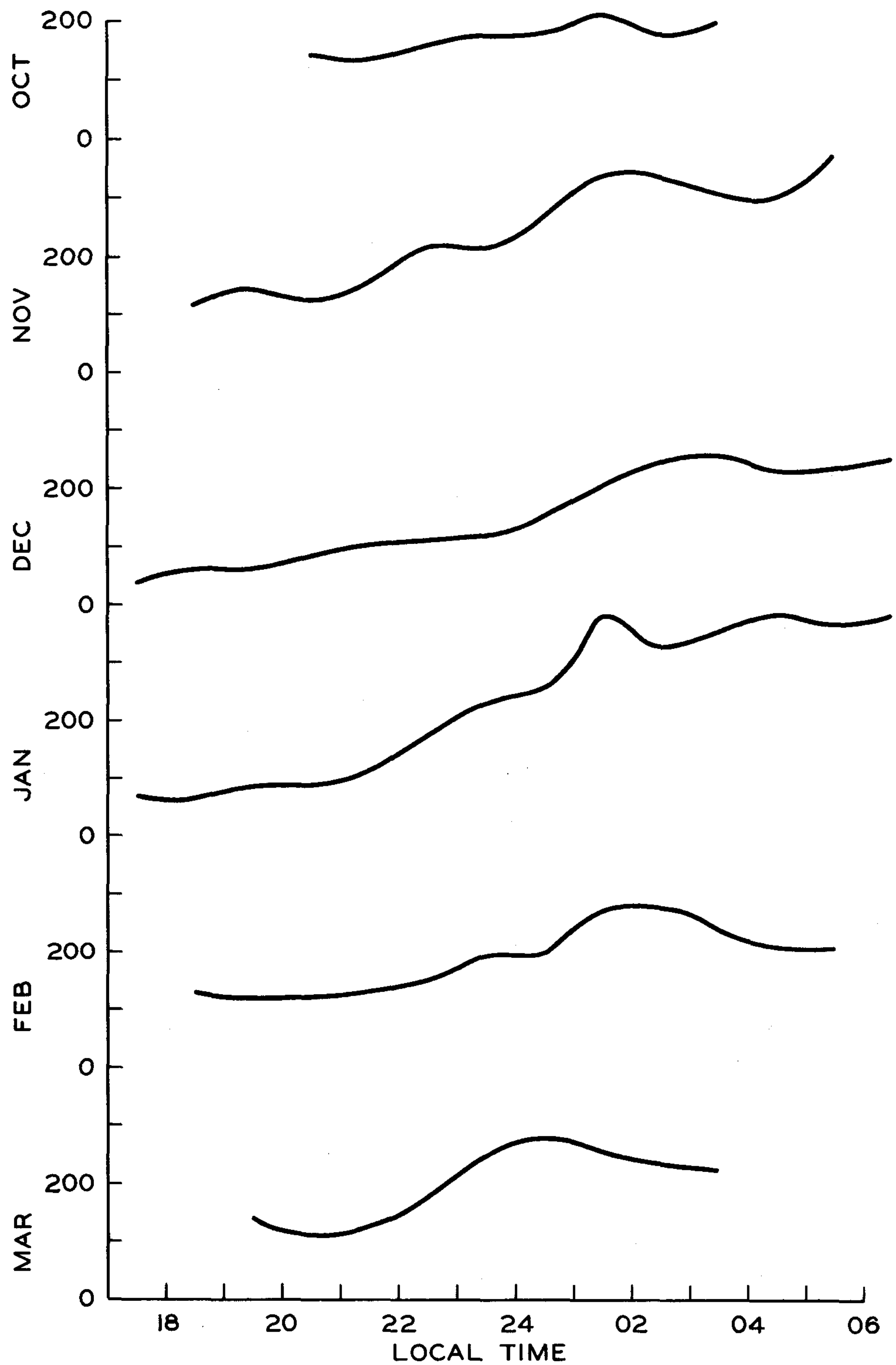

Fig. 2. Monthly Diurnal Variation Curves, 1955-56
3914 Luminosity Sky

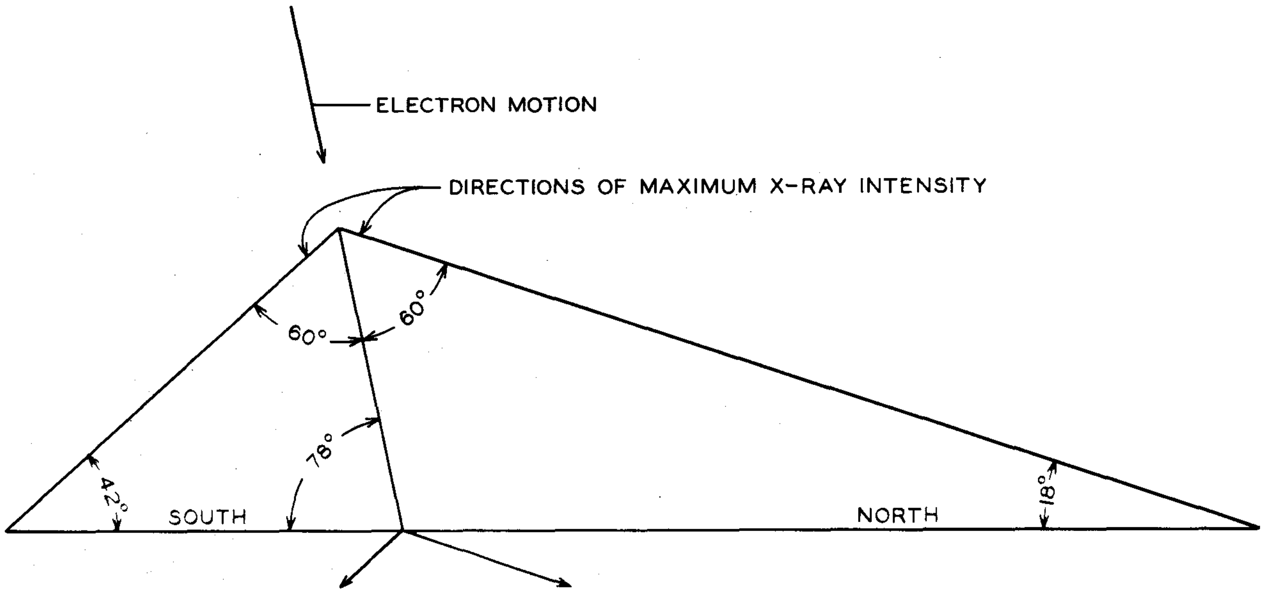

Fig. 3. Probable Geometry of Bremsstrahlung from Auroral Electrons. Because the Aurora is a Sheet Source, the 120° Cone will be filled, but because the Electron Motion is not Vertical, the Horizontal Flux is Asymmetric.